

Double and Linear Seesaw from Left-Right and Peccei-Quinn Symmetry Breaking

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In the left-right symmetric models, we can take the left-right symmetry to be the charge-conjugation and then impose a global symmetry under which the left- and right-handed fermion doublets carry equal but opposite charges. Consequently, we may introduce two Higgs bi-doublets to give the desired fermion mass spectrum. The global symmetry is identified to a Peccei-Quinn symmetry. We can introduce a complex scalar singlet to break the global Peccei-Quinn symmetry at a high scale. This symmetry breaking is also responsible for generating the heavy Majorana masses of the fermion singlets which have Yukawa couplings with the lepton and Higgs doublets. In this context, we can realize the double and linear seesaw to naturally explain the small neutrino masses. Our scenario can be embedded in the $SO(10)$ grand unification theories.

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I. INTRODUCTION

In the left-right symmetric models [1] based on the gauge group $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, the left-handed fermions are $SU(2)_L$ doublets as they are in the $SU(3)_c \times SU(2)_L \times U(1)_Y$ standard model (SM) while the right-handed fermions (the SM right-handed fermions plus the right-handed neutrinos) are placed in $SU(2)_R$ doublets. Usually, we need a Higgs bi-doublet to construct the Yukawa interactions between the left- and right-handed fermion doublets for generating the Dirac masses of the SM fermions. As for the small neutrino masses, they are given by the seesaw [2, 3], which also accommodates the leptogenesis [4] to explain the matter-antimatter asymmetry in the universe. For example, we can extend the original left-right symmetric model [1], where the Higgs scalars include one bi-doublet and two doublets, by introducing three fermion singlets with a Majorana mass term. In the presence of the Yukawa couplings of the fermion singlets to the lepton and Higgs doublets, we can obtain the double/inverse [5, 6] and linear [7] seesaw for generating the small neutrino masses to revive the original left-right symmetric model [8].

The left-right symmetry can be the parity or the charge-conjugation. In the case that the left-right symmetry is the charge-conjugation, we can impose a global symmetry under which the left- and right-handed fermion doublets carry equal but opposite charges. In this context, the global symmetry should be explicitly broken to generate the neutrino and charged fermion masses. For example [9], the global symmetry breaking can naturally make the fermion singlets, which have the Yukawa couplings with the fermion and Higgs doublets, to obtain the heavy masses for realizing the universal seesaw [10–13]. Since the global symmetry is mediated to the SM quarks, it can be identified to the Peccei-Quinn [14] (PQ) symmetry, which predicts the axion [14, 15] to solve the

strong CP problem.

In this paper we will revive the original left-right symmetric model by the PQ symmetry breaking. Specifically we will take the left-right symmetry to be the charge-conjugation and then assign the equal but opposite PQ charges for the left- and right-handed fermion doublets. We then need two Higgs bi-doublets to generate the desired fermion masses. This structure definitely will induce the Peccei-Quinn-Weinberg-Wilczek (PQWW) axion [14, 15]. To make the axion invisible, we will further introduce a complex scalar singlet for the PQ symmetry breaking, as did in the Kim-Shifman-Vainshtein-Zakharov [16] (KSVZ) model and the Dine-Fischler-Srednicki-Zhitnitsky [17] (DFSZ) model. After the PQ symmetry breaking, the fermion singlets can obtain their heavy Majorana masses to realize the double and linear seesaw. Our scenario can be embedded in the $SO(10)$ grand unification theories (GUTs).

II. THE MODEL

The scalar fields include two Higgs bi-doublets,

$$\begin{aligned}\phi_1(\mathbf{1}, \mathbf{2}, \mathbf{2}^*, 0) &= \begin{bmatrix} \phi_{11}^0 & \phi_{12}^+ \\ \phi_{11}^- & \phi_{12}^0 \end{bmatrix}, \\ \phi_2(\mathbf{1}, \mathbf{2}, \mathbf{2}^*, 0) &= \begin{bmatrix} \phi_{21}^0 & \phi_{22}^+ \\ \phi_{21}^- & \phi_{22}^0 \end{bmatrix},\end{aligned}\tag{1}$$

two Higgs doublets,

$$\begin{aligned}\chi_L(\mathbf{1}, \mathbf{2}, \mathbf{1}, -1) &= \begin{bmatrix} \chi_L^0 \\ \chi_L^- \end{bmatrix}, \\ \chi_R(\mathbf{1}, \mathbf{1}, \mathbf{2}, -1) &= \begin{bmatrix} \chi_R^0 \\ \chi_R^- \end{bmatrix},\end{aligned}\tag{2}$$

and one complex singlet,

$$\sigma(\mathbf{1}, \mathbf{1}, \mathbf{1}, 0).\tag{3}$$

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In the fermion sector, there are three neutral fermion singlets,

$$S_R(\mathbf{1}, \mathbf{1}, \mathbf{1}, 0), \quad (4)$$

besides three generations of quark and lepton doublets,

$$q_L(\mathbf{3}, \mathbf{2}, \mathbf{1}, \frac{1}{3}) = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad q_R(\mathbf{3}, \mathbf{1}, \mathbf{2}, \frac{1}{3}) = \begin{bmatrix} u_R \\ d_R \end{bmatrix}, \quad (5)$$

$$l_L(\mathbf{1}, \mathbf{2}, \mathbf{1}, -1) = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}, \quad l_R(\mathbf{1}, \mathbf{2}, \mathbf{1}, -1) = \begin{bmatrix} \nu_R \\ e_R \end{bmatrix}.$$

As the left-right symmetry is the charge-conjugation, the scalars and fermions will transform as

$$\phi_{1,2} \leftrightarrow \phi_{1,2}^T, \quad \chi_L \leftrightarrow \chi_R^*, \quad \sigma \leftrightarrow \sigma, \quad (6)$$

$$q_L \leftrightarrow q_R^c, \quad l_L \leftrightarrow l_R^c, \quad S_R \leftrightarrow S_R.$$

We further impose a global symmetry, under which the fields carry the quantum numbers as below

$$\begin{aligned} 1 & \text{ for } q_L, q_R^c, l_L, l_R^c, S_R; \\ 2 & \text{ for } \phi_1, \phi_2, \sigma^*; \\ 0 & \text{ for } \chi_L, \chi_R. \end{aligned} \quad (7)$$

The full scalar potential then should be

$$\begin{aligned} V = & \mu_\sigma^2 |\sigma|^2 + \mu_\chi^2 (|\chi_L|^2 + |\chi_R|^2) + \mu_{ij}^2 \text{Tr}(\phi_i^\dagger \phi_j) \\ & + \lambda_\sigma |\sigma|^4 + \lambda_\chi (|\chi_L|^4 + |\chi_R|^4) + \lambda'_\chi |\chi_L|^2 |\chi_R|^2 \\ & + \lambda_{ijkl} \text{Tr}(\phi_i^\dagger \phi_j) \text{Tr}(\phi_k^\dagger \phi_l) + \lambda'_{ijkl} \text{Tr}(\phi_i^\dagger \tilde{\phi}_j) \text{Tr}(\tilde{\phi}_k^\dagger \phi_l) \\ & + \kappa_{\sigma\chi} |\sigma|^2 (|\chi_L|^2 + |\chi_R|^2) + \rho_{ij} |\sigma|^2 \text{Tr}(\phi_i^\dagger \phi_j) \\ & + \xi_{ij} (|\chi_L|^2 + |\chi_R|^2) \text{Tr}(\phi_i^\dagger \phi_j) \\ & + \xi'_{ij} (\chi_L^\dagger \phi_i \phi_j^\dagger \chi_L + \chi_R^\dagger \phi_i^T \phi_j^* \chi_R^*) + [\alpha_{ij} \sigma^2 \text{Tr}(\tilde{\phi}_i^\dagger \phi_j) \\ & + \beta_i \sigma \chi_L^\dagger \phi_i \chi_R + \gamma_i \sigma^* \chi_L^\dagger \tilde{\phi}_i \chi_R + \text{H.c.}]. \end{aligned} \quad (8)$$

We also give the allowed Yukawa interactions,

$$\begin{aligned} \mathcal{L}_Y = & -y_q^i \bar{q}_L \phi_i q_R - y_l^i \bar{l}_L \phi_i l_R - h(\bar{l}_L \chi_L S_R + \bar{l}_R \chi_R^* S_R) \\ & - \frac{1}{2} g \sigma \bar{S}_R S_R^c + \text{H.c.} \end{aligned} \quad (9)$$

Clearly, the lepton and quark doublets, the Higgs doublets, the Higgs bi-doublets, the fermion singlets and the scalar singlet can, respectively, belong to the $\mathbf{16}_{F_i}$, $\mathbf{16}_H$, $\mathbf{10}_{H_{1,2}}$, $\mathbf{1}_{F_i}$ and $\mathbf{1}_H$ representation in the $SO(10)$ GUTs.

The symmetry breaking pattern is expected to be

$$\begin{aligned} & SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_{\text{PQ}} \\ & \quad \downarrow \langle \sigma \rangle \\ & SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ & \quad \downarrow \langle \chi_R \rangle \\ & SU(3)_c \times SU(2)_L \times U(1)_Y \\ & \quad \downarrow \langle \phi_{1,2} \rangle \\ & SU(3)_c \times U(1)_{em}. \end{aligned} \quad (10)$$

We denote the VEVs by

$$\begin{aligned} \langle \sigma \rangle = \frac{f}{\sqrt{2}}, \quad \langle \chi_R \rangle = \begin{bmatrix} \frac{v_R}{\sqrt{2}} \\ 0 \end{bmatrix}, \quad \langle \chi_L \rangle = \begin{bmatrix} \frac{v_L}{\sqrt{2}} \\ 0 \end{bmatrix}, \\ \langle \phi_1 \rangle = \begin{bmatrix} \frac{v_{11}}{\sqrt{2}} & 0 \\ 0 & \frac{v_{12}}{\sqrt{2}} \end{bmatrix}, \quad \langle \phi_2 \rangle = \begin{bmatrix} \frac{v_{21}}{\sqrt{2}} & 0 \\ 0 & \frac{v_{22}}{\sqrt{2}} \end{bmatrix}, \end{aligned} \quad (11)$$

which can be derived from the potential (8). Note that v_{11} , v_{12} , v_{21} , v_{22} and v_L should fulfill

$$v = \sqrt{v_{11}^2 + v_{12}^2 + v_{21}^2 + v_{22}^2 + v_L^2} \simeq 246 \text{ GeV}. \quad (12)$$

III. PECCEI-QUINN SYMMETRY

After the complex scalar singlet σ develops a VEV to spontaneously break the global symmetry, it can be described by

$$\sigma = \frac{1}{\sqrt{2}}(f + \rho) \exp\left(i \frac{a}{f}\right). \quad (13)$$

Here ρ is the physical boson while a is the Nambu-Goldstone boson (NGB). In the presence of the α, β, γ -terms in the potential (8), like the structure of the DFSZ [17] model, the NGB a can couple to the quarks,

$$\mathcal{L} \supset -\frac{1}{2f} (\partial_\mu a) \sum_q \bar{q} \gamma^\mu \gamma_5 q. \quad (14)$$

Therefore, through the color anomaly [18], the NGB a can pick up a tiny mass [15, 19],

$$m_a^2 = N^2 \frac{Z}{(1+Z)^2} \frac{f_\pi^2}{f^2} m_\pi^2, \quad (15)$$

where $N = 3$ for three families of the SM quarks while $Z \simeq m_u/m_d$. Clearly, the global symmetry is the PQ symmetry while the NGB becomes a pseudo NGB (pNGB)—the axion. We can conveniently express the axion mass as

$$m_a = \frac{\sqrt{Z}}{(1+Z)} \frac{f_\pi}{f_a} m_\pi \simeq 6.2 \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right), \quad (16)$$

where f_a is the axion decay constant. The PQ symmetry should be broken at a high scale to fulfill the theoretical and experimental constraints [20]. For example, the PQ symmetry breaking may happen before the inflation [21] to avoid the cosmological domain wall problem [22]. With an appropriate f_a the axion can act as the dark matter [23, 24].

IV. DOUBLE AND LINEAR SEESAW

After the symmetry breaking (10), the fermions will obtain their mass terms by their Yukawa couplings.

Specifically, the quarks and charged leptons can have the usual 3×3 Dirac mass matrices, i.e.

$$\mathcal{L} \supset -\tilde{m}_u \bar{u}_L u_R - \tilde{m}_d \bar{d}_L d_R - \tilde{m}_e \bar{e}_L e_R + \text{H.c.}, \quad (17)$$

with

$$\begin{aligned} \tilde{m}_u &= \frac{1}{\sqrt{2}} y_q^1 v_{11} + \frac{1}{\sqrt{2}} y_q^2 v_{21}, \\ \tilde{m}_d &= \frac{1}{\sqrt{2}} y_q^1 v_{12} + \frac{1}{\sqrt{2}} y_q^2 v_{22}, \\ \tilde{m}_e &= \frac{1}{\sqrt{2}} y_l^1 v_{12} + \frac{1}{\sqrt{2}} y_l^2 v_{22}. \end{aligned} \quad (18)$$

As for the neutral fermions including the left- and right-handed neutrinos and the fermion singlets, they will form a symmetric 9×9 mass matrix as below,

$$\begin{aligned} \mathcal{L} &\supset -\tilde{m}_\nu \bar{\nu}_L \nu_R - \frac{1}{\sqrt{2}} h v_L \bar{\nu}_L S_R - \frac{1}{\sqrt{2}} h v_R \bar{\nu}_R^c S_R \\ &\quad - \frac{1}{2} M_S \bar{S}_R^c S_R + \text{H.c.}, \\ &= -\frac{1}{2} \begin{bmatrix} \bar{\nu}_L \\ \bar{\nu}_R^c \\ \bar{S}_R^c \end{bmatrix}^T \begin{bmatrix} 0 & \tilde{m}_\nu & \frac{h v_L}{\sqrt{2}} \\ \tilde{m}_\nu^T & 0 & \frac{h v_R}{\sqrt{2}} \\ \frac{h^T v_L}{\sqrt{2}} & \frac{h^T v_R}{\sqrt{2}} & M_S \end{bmatrix} \begin{bmatrix} \nu_L^c \\ \nu_R \\ S_R \end{bmatrix} \\ &\quad + \text{H.c.}, \end{aligned} \quad (19)$$

with

$$\tilde{m}_\nu = \frac{1}{\sqrt{2}} y_l^1 v_{11} + \frac{1}{\sqrt{2}} y_l^2 v_{21}, \quad M_S = \frac{1}{\sqrt{2}} g f. \quad (20)$$

For $\frac{1}{\sqrt{2}} h v_R$ and/or M_S much bigger than \tilde{m}_ν and $\frac{1}{\sqrt{2}} h v_L$, we can make use of the seesaw formula [2] to derive the neutrino masses,

$$\mathcal{L} \supset -\frac{1}{2} m_\nu \bar{\nu}_L \nu_L^c + \text{H.c.}, \quad (21)$$

where the mass matrix m_ν contains two parts,

$$m_\nu = \tilde{m}_\nu \frac{1}{\frac{1}{\sqrt{2}} h^T v_R} M_S \frac{1}{\frac{1}{\sqrt{2}} h v_R} \tilde{m}_\nu^T - (\tilde{m}_\nu + \tilde{m}_\nu^T) \frac{v_L}{v_R}. \quad (22)$$

The first term is the double seesaw [5, 6] for $M_S \gg \frac{1}{\sqrt{2}} h v_R$ or the inverse seesaw [6] for $M_S \ll \frac{1}{\sqrt{2}} h v_R$. Clearly, the double seesaw should be our choice because of the large PQ symmetry breaking scale. As for the second term, it is the linear seesaw [7]. We can understand the double and linear seesaw by Fig. 1. In the double and linear seesaw context, the leptogenesis [4] can be realized by the decays of the right-handed neutrinos [8].

V. SUMMARY

In this paper we embedded the PQ symmetry in a left-right symmetric theory and then in an $SO(10)$ GUT. In our model, the left- and right-handed fermion doublets can naturally carry equal but opposite PQ charges because the left-right symmetry is the charge-conjugation. This implies we need two Higgs bi-doublets with the PQ charge so that the fermions can obtain a desired mass spectrum. The PQ symmetry breaking is driven by a complex scalar singlet at a high scale. The invisible axion can pick up a tiny mass through the color anomaly. In our model, the PQ symmetry breaking is also responsible for generating the heavy Majorana masses of the fermion singlets to realize the double and linear seesaw. Therefore, the neutrino mass-generation is naturally related to the PQ symmetry breaking [25].

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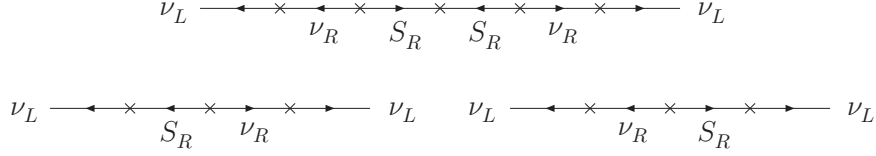


FIG. 1: Double seesaw (top) and linear seesaw (bottom).

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